

USARIEM TECHNICAL REPORT T-01/9

HEAT STRESS WHEN WEARING BODY ARMOR

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Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USMRMC Regulation 70-25 on Use of Volunteers in Research.

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13. ABSTRACT (Maximum 200 words) This study evaluated the heat strain induced by six configurations of a new modular body armor (MBA) design. Tests were conducted in two environments differing only by wind speed. The environments were 40°C (104°F), 20% rh, wind speeds 1.0 msec-1 (2.2 mph) and 2.5 msec-1 (5.6 mph). The environments were chosen to maximize evaporative capacity. Six male subjects completed 12 experiments. The armor was worn at three wear levels: open in front (F), open at the sides (S) and fully closed (C); and at two protection levels: partial armor (P) and total armor (T). The six configurations were (1) MBA open in front, no shoulder or collar armor (FP); (2) MBA open at the sides, no shoulder or collar armor (SP); (3) MBA fully closed, no shoulder or collar armor (CP); (4) MBA open in front, all armor in place (FT); (5) MBA open at the sides, all armor in place (ST); and (6) MBA fully closed, all armor in place (CT). Each day, subjects stood for a 5-minute rest, and walked for 100 minutes on a treadmill at approximately 425 watts (moderate exercise). There were no significant differences in final core temperatures, final heart rates, rates of heat storage, sweating rates, and evaporative heat loss among the armor configurations in either environment. These results indicate that design changes allowing the armor to be worn at either open wear level and allowing for the removal of shoulder and collar armor do not effect heat loss under the conditions tested. These findings cannot be applied to high humidity environments or high work intensities.				
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EXECUTIVE SUMMARY

The purpose of this study was to evaluate the heat strain induced by six configurations of a new modular body armor (MBA) design. Each configuration was tested in two environmental conditions. The two environments were 40°C (104°F), 20% rh, wind speed 1.0 m•sec⁻¹ (2.2 mph); and 40°C, 20% rh, 2.5 m•sec⁻¹ (5.6 mph).

WBGT, based on wet bulb and dry bulb temperatures, was 27.8°C for the experiments.

The environments were chosen to maximize evaporative capacity. Six male subjects completed all 12 experiments. The armor was worn at three wear levels: open in front (F), open at the sides (S) and fully closed (C); and at two protection levels: partial armor (P) and total armor (T). The six configurations were (1) MBA open in front, no shoulder or collar armor (FP); (2) MBA open at the sides, no shoulder or collar armor (SP); (3) MBA fully closed, no shoulder or collar armor (CP); (4) MBA open in front, all armor in place (FT); (5) MBA open at the sides, all armor in place (ST); and (6) MBA fully closed, all armor in place (CT). In each experiment, subjects stood for a 5-minute rest, and then walked for 100 minutes on a treadmill at approximately 425 watts (moderate exercise). Final core temperatures in the 1.0 m•sec⁻¹ wind speed environment were FP=38.2±0.3°C, SP=38.3±0.3°C, CP=38.3±0.2°C, FT=38.3±0.2°C, ST=38.3±0.2°C and CT=38.3±0.3°C. Final heart rates in the 1.0 m•sec⁻¹ wind speed environment were FP=129±16 b•min⁻¹, SP=136±20 b•min⁻¹, CP=134±19 b•min⁻¹, FT=133±14 b•min⁻¹, ST=132±17 b•min⁻¹, and CT=134±19 b•min⁻¹. Final core temperatures in the 2.5 m•sec⁻¹ wind speed environment were FP=38.1±0.3°C, SP=38.2±0.5°C, CP=38.2±0.3°C, FT=38.1±0.4°C, ST=38.2±0.3°C, and CT=38.1±0.3°C. Final heart rates in the 2.5 m•sec⁻¹ wind speed environment were FP=125±14 b•min⁻¹, SP=134±26 b•min⁻¹, CP=128±21 b•min⁻¹, FT=131±16 b•min⁻¹, ST=126±16 b•min⁻¹, and CT=126±4 b•min⁻¹. There were no significant differences in final core temperatures, final heart rates, rates of heat storage, sweating rates, and evaporative heat loss among the six armor configurations in either environment. There were no differences in the ability to dissipate the heat induced by the different configurations of MBA during moderate exercise in the two desert environments. These results indicate that design changes allowing the armor to be worn at either open wear level or without shoulder and collar armor do not affect heat loss under the conditions tested. Finally, these findings cannot be applied to high humidity environments or high work intensities.

INTRODUCTION

The future battlefield will require a highly mobile, rapidly deployed ground force. Soldiers comprising this force will face increasingly sophisticated weapons in addition to known environmental hazards. The lethal nature of this future battlefield will require soldiers to wear enhanced equipment to provide balanced multiple threat protection. The U.S. Army Natick Research, Development and Engineering Center (NRDEC) developed improved body armor as one component of this increased protection for the dismounted soldier. The objective of the improved armor design was to become an integral part of a modular fighting system for the dismounted soldier, and to improve combat effectiveness and enhance survivability against multiple battlefield hazards. The integrated modular body armor (MBA) system was developed to optimize the balance between performance and protection while minimizing heat strain. The modular design of the armor components is intended to allow commanders to determine the amount of soft armor and hard plates to be used at any time to minimize weight, reducing physiological impact and increasing mobility while still providing protection. Also, the armor is being developed concurrently with the new load bearing equipment, so they can be integrated together to increase soldier mobility. One potential trade off to minimize the heat strain was to design the MBA to be worn at an open wear level in tactical situations with a low potential for experiencing enemy fire. The current Personal Armor System for Ground Troops (PASGT) body armor is designed to be worn closed in tactical situations.

The U.S. Army and the U.S. Marine Corps are both interested in the MBA. Prototypes of the MBA are under development by both service branches. The basic soft components of both MBA prototypes provide protection from handguns and fragmentation. Both prototypes also feature removable front and back hard Kevlar plate components, providing additional protection from rifle bullets and flechette. Removable hard Kevlar plates are also a feature of the current PASGT armor. Both MBA prototypes have removable shoulder and collar soft armor components to minimize possible heat strain in certain tactical conditions where additional protection levels might be leveraged against mission effectiveness. Both developmental MBA systems address the potential benefit of reduced heat strain by designing the armor to be worn open in specific tactical circumstances. However, the Army prototype provides an opening along both sides under the arms, while the Marine prototype is a front opening design. A possible advantage to wearing the MBA at an open wear level is that an increased proportion of the torso would be accessible for heat loss to the environment. Any air movement over the additional exposed torso would potentially increase both convective and evaporative heat loss potential for the soldier wearing the encapsulating protective equipment.

The current environmentally controlled study was conducted to determine whether there would be a difference in heat strain incurred with the MBA worn at the

front and side open wear levels, worn fully closed, and worn with and without soft shoulder and collar armor. The developers requested testing in a hot, dry desert type environment with both low and moderate wind speeds to maximize the potential for evaporative cooling during the tests. They also requested information on the effects of a hot, humid jungle type environment on heat strain in the armor. Because the request for testing with shoulder and collar armor protection levels was an add-on to the original scope of the research, the developer withdrew the request for tests in humid environments. Therefore, human testing was conducted only in the hot, dry environments. Mathematical heat strain models were used to approximate the impact of wearing the MBA in a humid environment. The purpose of this study was to evaluate the heat strain induced by six configurations of a new MBA design. It was hypothesized that both the front and side open wear levels would provide equivalent reduction in heat strain. It was further hypothesized that heat strain would be greater when the armor was worn closed, and that the addition of the shoulder and collar armor protection level would have no increased impact on heat strain at either open or closed wear levels.

METHODS

SUBJECTS

Six male volunteers served as subjects and completed all phases of the study. All subjects were medically examined to assure there were no underlying medical problems. The mean \pm SD age, height, weights and % body fat of the subjects were 22 ± 6 years, 176 ± 6 cm, 76.3 ± 14.5 kg and 19.4 ± 6.1 % body fat (2). All subjects were fully informed of the purpose, procedures, and potential risks of the study and signed a statement of informed consent. Investigators adhered to guidelines established for research in humans in USARIEM M 70-68, AR 70-25 and USAMRMC 70-25 on the Use of Volunteers in Research.

PROCEDURES/MEASUREMENTS

Acclimation

The subjects completed a 7day, exercise-heat acclimation program, which standardized the heat acclimation level of the entire group and insured that changes in acclimation status did not occur during testing. Acclimation consisted of 100 minutes of treadmill walking each day at 45°C T_{db} , 20°C T_{dp} , (20% rh), 31.4°C WBGT, and wind speed $1.0 \text{ m}\cdot\text{sec}^{-1}$ (113°F T_{db} , 68°F T_{dp} , 88.5°F WBGT, wind speed 2.2 mph). Subjects dressed in shorts and sneakers. Heart rate (HR) and core temperature (T_{re}) were monitored throughout each session. Subjects drank sufficient water during each exercise-heat acclimation session to prevent progressive dehydration. Pre- and post-exercise weights were charted each day to monitor weight changes, and prior to daily release, subjects were supplied with sufficient fluids to return to their pre-exercise weights. This practice was continued throughout all heat exposures.

During the first 2 days of acclimation, treadmill speed and grade were varied, and the subjects' metabolic rates were measured by open circuit spirometry at each speed and grade combination (7). Combinations eliciting approximately 425 W of energy expenditure were used for acclimation. Speed and grade combinations eliciting approximately 375 W were used for the test sessions, allowing for an increased energy cost of approximately 50-60 W when wearing the full military uniform with MBA (3). The 425 W metabolic rate approximates the energy expenditure of soldiers walking at self-paced work for prolonged periods on varied terrain in the field (5), and is representative of a moderate work intensity of 375-500 W for a military task (9).

Experiments

Only the wind speed was varied in the two environmental conditions used for the experiments. The environments were hot and dry at 40°C (104°F), 20% rh, 27.8°C (82°F) WBGT with a low wind speed of 1.0 m•sec⁻¹ and a moderate wind speed of 2.5 m•sec⁻¹ (2.2 and 5.6 mph), no solar load. The differences between wind speeds did not impact the WBGT. The environments provided for a maximal evaporative power (E_{\max}) of 654 W at the 1.0 m•sec⁻¹ wind speed and 813 W at the 2.5 m•sec⁻¹ wind speed (8). As determined by the heat balance equation, the required evaporative cooling (E_{req}) for a nude subject exercising at this intensity under these environmental conditions is approximately 465 W. The ratio of E_{req}/E_{\max} was 71% for the low wind speed and 57% for the moderate wind speed. Subjects wore socks; underwear, the summer weight Temperate Battle Dress Uniform (TBDU), boots, Kevlar helmet and one of the six configurations (Table 1) of MBA in each experiment. The weight of all clothing and equipment worn during the experiments ranged from 8.3-9.5 kg in the partial protection level without shoulder and collar armor, and 8.7-10.1 kg in the total protection level. The configurations were tested in a counterbalanced design to avoid an order effect on results.

Table 1. The six configurations of modular body armor as worn in each of the two environmental conditions: low wind, 40°C, 20%rh, 1.0 m•sec⁻¹ wind speed; and moderate wind, 40°C, 20%rh, 2.5 m•sec⁻¹ wind speed.

	FRONT OPEN (F) CONFIGURATION	SIDE OPEN (S) CONFIGURATION	CLOSED (C) CONFIGURATION
PARTIAL ARMOR (P) NO SHOULDER OR COLLAR ARMOR	FP	SP	CP
TOTAL ARMOR (T) ALL ARMOR IN PLACE	FT	ST	CT

In each experiment, the subjects stood at rest for 5 minutes then completed 100 minutes of continuous treadmill walking at the speed and grade predetermined during the exercise-heat acclimation program. Each day, the subjects were given 300 ml of a commercial sport drink immediately after the nude weight taken at arrival. Subjects were encouraged to drink at least 300 ml of water every 20 minutes during exercise to prevent dehydration. Subjects always reported at the same starting time, with approximately 2 days between tests for recovery and rehydration.

During all tests, T_{re} was measured by a flexible thermistor probe inserted approximately 10 cm beyond the anal sphincter. During experiments, skin temperatures (T_{sk}) were measured with a six-site skin thermocouple harness (arm, chest, back, rib cage mid axillary, thigh, and calf). T_{re} and T_{sk} were obtained by a computerized data collection system. HR was obtained from Polar™ radio transmitter units and recorded every 5 minutes. Whole body sweating rate and evaporative cooling were calculated from the change in nude body weight during the entire exposure, with allowances for liquid ingested. Heat storage (S) in $W \cdot m^{-2}$ was calculated from the equation $S = [(m_b \cdot c_b) / A_D] \cdot (dT_b / dt)$, where m_b is the mean body weight (kg), during the experiment; c_b is the specific heat constant ($0.965 W \cdot h \cdot ^\circ C^{-1} \cdot kg^{-1}$); A_D is the DuBois surface area (m^2); dT_b is the change in mean body temperature ($^\circ C$) where $T_b = 0.2 \cdot T_{sk} + 0.8 \cdot T_{re}$; and dt is the exposure time (h) of the experiment. Metabolic rates were measured during exercise daily to assure the repeatability between days (7).

STATISTICAL ANALYSIS

T-tests were run on final core temperature and final heart rate after 100 minutes of exercise on Days 6 and 7 of acclimation to determine if there was a difference in

subject means between the days. All experimental test data were analyzed by ANOVA with repeated measures. The Tukey Test was used to isolate differences between configurations at the $p < 0.05$ level. Power analysis calculated prior to beginning of the study indicated that 12 subjects would be sufficient to assure the validity of the results. It was decided that no further testing would be required based on the results with the initial six subjects.

RESULTS

ACCLIMATION

It was determined that after 7 days the group was sufficiently acclimated to conduct experiments. Final core temperature on Day 6 was $38.1 \pm 0.2^\circ\text{C}$ and on Day 7 was $38.3 \pm 0.5^\circ\text{C}$, with no difference between days. Final heart rate on Day 6 was $124 \pm 15 \text{ b} \cdot \text{min}^{-1}$ and on Day 7 was $125 \pm 15 \text{ b} \cdot \text{min}^{-1}$, with no difference between days.

LOW WIND SPEED ($1.0 \text{ m} \cdot \text{sec}^{-1}$)

The mean \pm SD resting core temperatures and heart rates for the subjects prior to entering the chamber in each armor configuration were $37.12 \pm 0.39^\circ\text{C}$, $70 \pm 14 \text{ b} \cdot \text{min}^{-1}$ for FP; $37.21 \pm 0.36^\circ\text{C}$, $67 \pm 9 \text{ b} \cdot \text{min}^{-1}$ for SP; $37.25 \pm 0.40^\circ\text{C}$, $72 \pm 16 \text{ b} \cdot \text{min}^{-1}$ for CP; $37.16 \pm 0.30^\circ\text{C}$, $69 \pm 11 \text{ b} \cdot \text{min}^{-1}$ for FT; $37.18 \pm 0.24^\circ\text{C}$, $70 \pm 12 \text{ b} \cdot \text{min}^{-1}$ for ST; and $37.22 \pm 0.28^\circ\text{C}$, $71 \pm 6 \text{ b} \cdot \text{min}^{-1}$ for CT. Table 2 summarizes the findings of the subjects in all six armor configurations at the completion of the low wind condition. All subjects completed exercise in all armor configurations. There were no statistical differences in any final values of any of the physiological variables among the armor configurations.

Table 2. Mean \pm SD and range for endurance time and physiological response variables of subjects during exercise in the six modular body armor configurations at 40°C, 20% rh, wind speed 1.0 m•sec⁻¹.

	FP	SP	CP	FT	ST	CT
Endurance Time (min)	100	100	100	100	100	100
Final Core Temp (°C)	38.2 \pm 0.3 37.8-38.7	38.3 \pm 0.3 38.0-38.9	38.3 \pm 0.2 38.2-38.8	38.3 \pm 0.2 38.0-38.5	38.3 \pm 0.2 38.1-38.5	38.3 \pm 0.3 38.0-38.8
Heat Storage (W•m ⁻²)	22 \pm 7 14-31	22 \pm 9 15-39	24 \pm 5 19-33	24 \pm 5 18-31	20 \pm 5 14-28	22 \pm 4 18-30
Sweating Rate (g•min ⁻¹)	19 \pm 3 16-23	17 \pm 1 16-19	17 \pm 2 13-20	18 \pm 2 15-21	18 \pm 3 14-23	18 \pm 2 16-22
Evaporative Heat Loss (W•m ⁻²)	269 \pm 50 213-322	230 \pm 68 101-295	228 \pm 56 157-292	232 \pm 47 144-266	237 \pm 57 174-322	262 \pm 34 210-289
Heart Rate (b•min ⁻¹)	129 \pm 16 104-146	136 \pm 20 111-168	134 \pm 19 116-167	133 \pm 14 111-153	132 \pm 17 108-158	134 \pm 19 111-162

FP = Partial armor (no collar or shoulder armor) open in front; SP = Partial armor open on the sides; CP = partial armor fully closed; FT = Total armor (all components in place) open in front; ST = Total armor open on the sides; CT = Total armor fully closed.

MODERATE WIND SPEED (2.5 m•sec⁻¹)

The mean \pm SD resting core temperatures and heart rates for the subjects prior to entering the chamber in each armor configuration were 37.15 \pm 0.44°C, 64 \pm 12 b•min⁻¹ for FP; 37.20 \pm 0.47°C, 63 \pm 10 b•min⁻¹ for SP; 37.15 \pm 0.36°C, 68 \pm 8 b•min⁻¹ for CP; 37.19 \pm 0.50°C, 64 \pm 11 b•min⁻¹ for FT; 37.10 \pm 0.38°C, 64 \pm 9 b•min⁻¹ for ST; and 37.11 \pm 0.32°C, 65 \pm 7 b•min⁻¹ for CT. Table 3 summarizes the findings of the subjects in all six armor configurations at the completion of the moderate wind condition. All subjects completed exercise in all armor configurations. There were no statistical differences among the final values of any of the physiological variables in any of the armor configurations.

Table 3. Mean \pm SD and range for endurance time and physiological response variables of subjects during exercise in the six modular body armor configurations at 40°C, 20% rh, wind speed 2.5 m•sec⁻¹.

	FP	SP	CP	FT	ST	CT
Endurance Time (min)	100	100	100	100	100	100
Final Core Temp (°C)	38.1 \pm 0.3 37.7-38.6	38.2 \pm 0.5 37.7-39.0	38.2 \pm 0.3 37.9-38.6	38.1 \pm 0.4 37.8-38.6	38.2 \pm 0.3 37.8-38.5	38.1 \pm 0.3 37.9-38.6
Heat Storage (W•m ⁻²)	19 \pm 4 14-23	20 \pm 6 13-28	25 \pm 10 16-42	19 \pm 4 15-24	18 \pm 7 7-26	19 \pm 6 10-27
Sweating Rate (g•min ⁻¹)	18 \pm 2 15-22	18 \pm 2 17-21	18 \pm 2 16-20	18 \pm 2 16-21	18 \pm 2 15-20	21 \pm 4 17-28
Evaporative Heat Loss (W•m ⁻²)	276 \pm 46 201-321	280 \pm 39 215-325	257 \pm 32 215-300	270 \pm 47 211-319	263 \pm 51 181-327	287 \pm 53 206-372
Heart Rate (b•min ⁻¹)	125 \pm 14 110-150	134 \pm 26 108-183	128 \pm 21 102-160	131 \pm 16 109-157	126 \pm 16 113-153	126 \pm 4 104-153

FP = Partial armor (no collar or shoulder armor) open in front; SP = Partial armor open on the sides; CP = partial armor fully closed; FT = Total armor (all components in place) open in front; ST = Total armor open on the sides; CT = Total armor fully closed.

DISCUSSION

Modular body armor was developed to create a balance between providing required ballistic protection and reducing the effects of environmental heat stress in varying tactical situations. The requirement for the current study was to use a desert environment that would enhance evaporative cooling. The 40°C, 20% rh ambient temperature was chosen to allow for evaporative cooling in individuals unencumbered by highly insulative clothing and to allow for prolonged continuous exercise. The two wind speeds (1.0 and 2.5 m•sec⁻¹) were chosen to determine if the open configurations of the armor enhanced the evaporative potential provided by the wind. The E_{req} in the low wind environment was 71% of the E_{max} and was 57% of the E_{max} in the moderate wind environment. It has been shown that sweating rate declines fairly rapidly as skin wettedness increases between E_{req}/E_{max} ratios of 55% to 80%, so it was thought that there would be a decrease in evaporative cooling at the lower wind speed (4).

The results of this study indicate that the current design configurations of the MBA successfully minimized the impact of the environmental heat stress in the environments tested. Specifically, neither wearing the armor opened or closed, nor removing the shoulder and collar armor affected heat loss or physiologic strain during exercise. Regardless of the MBA configuration, the body surface area available for

evaporative heat loss was sufficient to maintain a low rate of heat storage. The MBA was designed to protect the torso (approximately 35% of the total body surface area), and even some of this area was left exposed. That uncovered area on the torso, plus the remaining exposed body surface area, allowed sufficient evaporative cooling with equivalent heat storage in all configurations in both environments. Under these conditions, the experimental results were not different from the results predicted by the USARIEM-exp heat strain model for equivalent heat strain wearing the warm weather BDU without armor (1). The USARIEM-exp model predicted core temperatures of 38.4°C in the low wind environment and 38.3°C in the moderate wind environment after 100 minutes of exercise.

There was no difference between the open and closed wear levels in this test because of the high level of evaporative cooling in both environments. It is possible that in an environment with a lower E_{max} (i.e., temperate summer; 30°C [86°F], 50% rh), a difference might be observed between open and closed wear levels. However, it is also possible that exposure to a less extreme hot environment would result in no difference between open and closed wear levels. This is because the armor was held close to the chest even when worn open. This configuration provided ballistic protection for front and side open wear levels, because elastic straps prevented the armor from flapping freely as the subjects walked. While it had no effect on the current test, these open wear levels limited the amount of free airflow across the torso and minimized the potential advantage of an open wear level in an environment with lower E_{max} .

Humid environments were excluded from the current tests, as the lack of evaporative cooling possible in a tropic environment (35°C [95°F], 75% rh) would severely limit performance due to the high level of heat strain so much so that any benefit from an open armor configuration would be negligible. Mathematical predictions for this tropic condition with low and moderate winds, with the USARIEM-exp model using metabolic rates similar to the current test, indicated core temperatures of 39.0°C at the low wind speed and 38.7°C at the moderate wind speed after 100 minutes of exercise wearing the warm weather BDU. An additional prediction adding soft armor flak vests worn open with the desert BDU (closest available configuration to that tested) increased the core temperature values by 0.1°C at each wind speed. These levels of heat strain would be withstood by a small percentage of soldiers, and any additional increase in heat strain from the MBA and warm weather BDU would increase the casualty rate under such conditions (7). Modeling the desert BDU worn with flak vest in a closed configuration in a tropic environment predicted core temperatures of 39.6°C at low wind and 39.4°C at moderate wind after 100 minutes of exercise. It is apparent that while wearing armor open in a tropic environment attenuates the increase in core temperature (up to 0.6°C), the heat stress of the environment alone will override any benefit.

If soldiers carried a heavier load requiring an increased metabolic cost (such as an approach march), the rate of heat storage would increase proportionally. It is possible that at these high work intensities there might be a small thermoregulatory benefit to wearing the MBA at an open wear level, but the increased load will also increase insulation and decrease permeability of the entire clothing/equipment system, perhaps compromising any gain. Further evaluation would be indicated for soldiers carrying a full combat load if the final MBA system design does allow for an open wear level.

The similar physiological responses observed during short-term work indicate that heat loss is not impaired by the additional collar and shoulder armor (FT versus FP; ST versus SP; and CT versus CP). The current findings are in agreement with a controlled environmental study on varied configurations of the Australian Army's armor tested in hot environments (Eggleston and Amos, Unpublished, 1997). The additional body surface area covered by the collar and shoulder armor is quite small compared to the body surface area available for evaporative heat loss. Therefore, there is minimal effect on the rate of heat storage in the environmental conditions of these studies. The Australian study and the current research do not guarantee that soldiers carrying full field loads and performing military tasks in varied environmental conditions will not be affected by the addition of shoulder and collar components.

A 5°F WBGT penalty is traditionally added to the environmental conditions when soldiers go to the field wearing body armor. Based on the results of this study and the above mathematical models, that penalty is not necessary in desert conditions when wearing the MBA. However, both the limited environmental conditions and single metabolic rate used in this study minimize the ability to globalize the findings.

Wearing the MBA in all configurations does have an impact on water requirements of soldiers exercising in a desert environment. The 27.8°C (82°F) WBGT environment for the current experiment falls within in the range of the U.S. Army's Heat Category 2 training standards (82 – 84.9°F WBGT) (6). Recently developed fluid replacement tables indicate soldiers can perform moderate work in this heat category and maintain a core temperature less than 38.5°C for up to 4 hours wearing the warm weather BDU at work-rest cycles of 50/10 minutes per hour (6). The fluid replacement tables indicate that soldiers would require water intake of approximately 750 ml per hour while following this regimen. Subjects in the current MBA study completed 100 minutes of moderate exercise and maintained a core temperature under 38.5°C while wearing the armor in all configurations. However, sweating rates demonstrated water replacement requirements of 1080 ml per hour. If soldiers wearing the MBA followed the recommended 50/10 work rest cycle to allow for 4 hours of work, sweating rate would decrease, but water requirements would still be greater than 900 ml per hour. It is possible that even though the six configurations of the MBA did not alter heat strain in

the desert environments, water requirements were increased (by at least 20%) relative to performing equivalent work wearing only the warm weather BDU.

CONCLUSION

In summary, there were no significant differences in the ability to dissipate metabolic heat among the various configurations of MBA worn during 100 minutes of moderate exercise in two desert environments. These results indicate that design changes allowing the armor to be worn at either open wear level or without shoulder and collar armor do not affect heat loss under the conditions tested. Finally, these findings cannot be applied to high humidity environments or high work intensities.

REFERENCES

1. Cadarette, B. S., S. J. Montain, M. A. Kolka, L. A. Stroschein, W. T. Matthew, and M. N. Sawka. Cross validation of USARIEM heat strain prediction models. *Aviat. Space Environ. Med.* 70: 996-1006, 1999.
2. Durnin, J. V. G. A., and J. Womersley. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *J. Br. Nutr.* 32: 77-97, 1974.
3. Givoni, B., and R. F. Goldman. Predicting metabolic energy cost. *J. Appl. Physiol.* 30: 429-433, 1971.
4. Gonzalez, R. R., K. B. Pandolf, and A. P. Gagge. Heat acclimation and decline in sweating during humidity transients. *J. Appl. Physiol.* 36: 419-425, 1974.
5. Levine, L., W. J. Evans, F. R. Winsmann, and K. B. Pandolf. Prolonged self-paced hard physical exercise comparing trained and untrained men. *Ergonomics* 25: 393-400, 1982.
6. Montain, S. J., W. A. Latzka, and M. N. Sawka. Fluid replacement recommendations for training in hot weather. *Mil. Med.* 164: 502-508, 1999.
7. Montain, S. J., M. N. Sawka, B. S. Cadarette, M. D. Quigley, and J. M. McKay. Physiological tolerance to uncompensable heat stress: effects of exercise intensity, protective clothing and climate. *J. Appl. Physiol.* 77: 216-222, 1994.
8. Nishi, Y. Convective heat transfer coefficient for various activities and environment. *Arch. Sci. Physiol.* 27 (No. 2): A59-A66, 1973.
9. Pandolf, K. B., L. A. Stroschein, L. L. Drolet, R. R. Gonzalez, and M. N. Sawka. Prediction modeling of physiological responses of human performance in the heat. *Comput. Biol. Med.* 16: 319-329, 1986.